Teaching process engineering fundamentals using an ice cream maker

Gönül Kaletunç, Kevin Duemmel, and Christopher Gecik, Food Agricultural and Biological Engineering, The Ohio State University, 590 Woody Hayes Drive, Columbus, OH 43210

Abstract

A number of engineering and science concepts can be illustrated with ice cream processing. The ingredient combinations as well as the processing conditions can affect the final physical properties of the ice cream which are judged by the consumer in terms of the textural and sensory attributes of the product.

The ice cream laboratory experiment is designed as an application of several concepts that sophomore level engineering students learn. The ice cream laboratory has a pre-lab assignment that requires students to develop an ice cream formulation within given constraints of available ingredients and percentages of fat, carbohydrate, and protein in the final product. In the pre-lab assignment the students apply the material balance concept and solve simultaneous linear equations to determine the ice cream formulation. During the experiments, students use a one liter electric home ice cream maker modified in our laboratory with instruments to measure temperature, mixing speed, and mixing torque. Students analyze the collected data to determine the heat energy requirement, mixing power requirement, and the viscosity of the ice cream. The experiment provides an opportunity to discuss and illustrate several engineering and science topics including, material and energy balances, heat transfer, freezing, mass transfer, mixing, viscosity, and freezing point depression.

The same set-up also is used in the program “Science and Engineering of Ice Cream” to introduce high school science teachers to an education tool that can be used for their students to explore engineering concepts.

Introduction

Processing of food materials provides excellent opportunities for grade school as well as college students to learn science and engineering concepts with an incentive for consuming the final product. We chose to utilize ice cream processing for students to explore and discover applications of various engineering and science concepts while being excited with the anticipation of tasting the ice cream.

We plan to teach the engineering and science concepts illustrated in Figures 1 and 2.

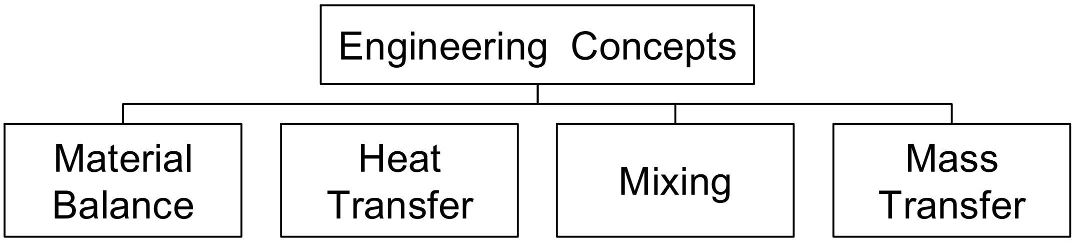


Figure 1. Engineering concepts emphasized.

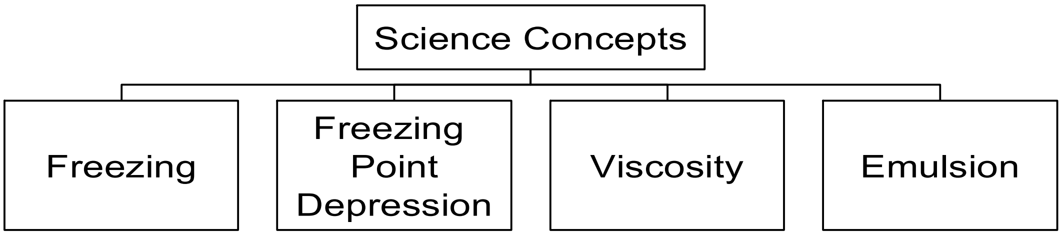


Figure 2. Science concepts emphasized.

Materials and Methods

Materials: Ice cream ingredients used are heavy cream (36% fat), whole milk (3.2% fat), sugar, vanilla extract, and salt.

Equipment: An electric powered ice cream maker (Cuisinart ICE-20, Denver, CO) is used to make ice cream (Figure 3). The ice cream maker was modified to allow us to collect the rotational speed (rpm) and force required for rotation (Newtons).

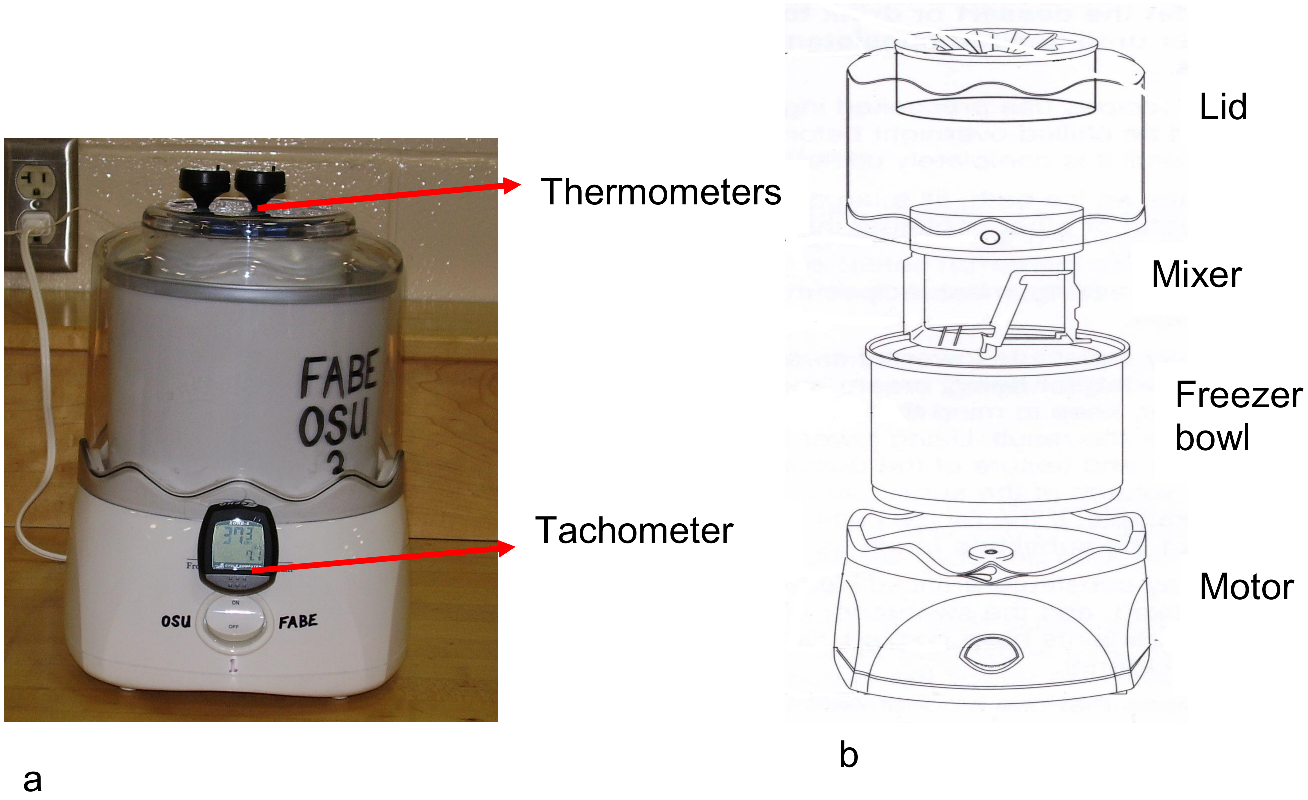


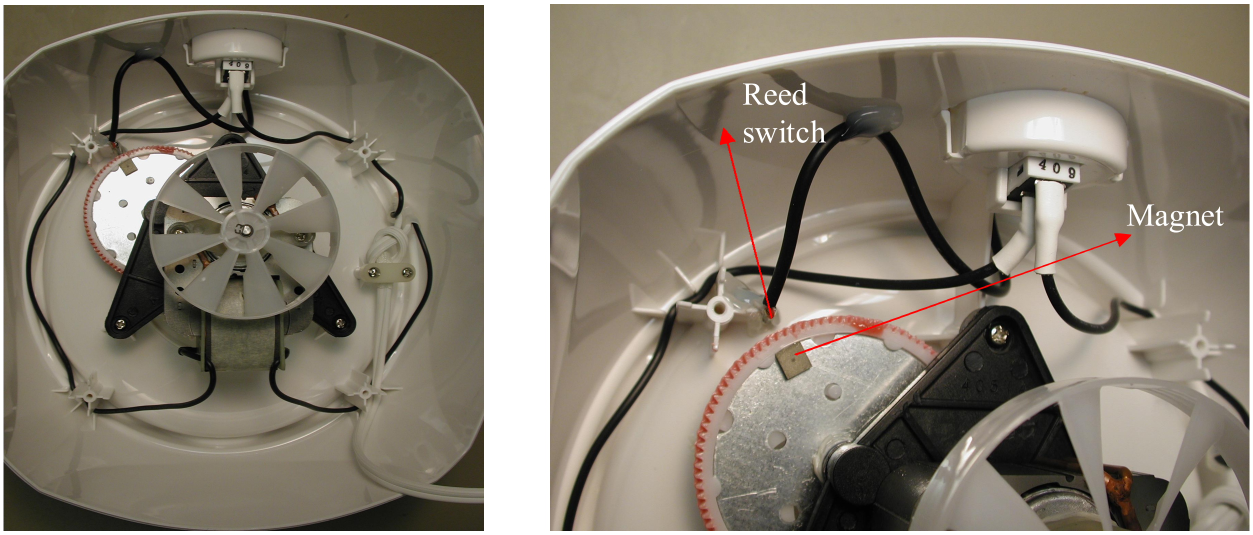
Figure 3. Electric powered modified a) ice cream maker, b) parts

Temperature measurement: Two digital thermometers (Taylor TruTemp, #3516, Oak Brook, IL) were used to measure the temperature of ice cream mixture at the center and at the surface of the freezer bowl. To secure the thermometers in place, a mold was cast from silicone (RTV 664, GE Silicones, Waterford, NY) through which thermometers were inserted (Figure 4). The mold was fitted to the opening in the lid.

a b

Figure 4. a) Thermometers inserted through mold, b) mold inserted in ice cream maker lid

Modifications for rotational speed measurement: The ice cream maker rotates the freezer bowl at 38 rpm and slows down slightly as the ice cream mixture thickens. Figure 5a shows the bottom view of ice cream maker. A bicycle computer (Echowell Zone 5) was purchased for use as a tachometer. The bicycle computer displays rpm (displayed as km/hr) by counting pulses that are created by a permanent magnet that repeatedly rotates past a reed switch. The pulses are multiplied by the bicycle wheel's circumference within the computer to determine speed. An accessible gear inside the ice cream maker was chosen to carry a small permanent magnet that rotated by the reed switch. An appropriate "wheel circumference" is calculated by counting the number of teeth on the gears driving the rotating output hub, along with a scaling factor to display rpm as km/hr. The circumference of "2445 mm" was calculated based on the gear chosen to carry the magnet in the ice cream maker.



a b

Figure 5: a) bottom view of ice cream maker, b) added reed switch and magnet

A small permanent magnet stuck (via magnetism) to the metal hub of a gear. Immediately adjacent to the magnet is the reed switch that counts the rotation of the gear. Figure 5b shows a close-up photo of the mounting location of the reed switch and permanent magnet. The reed switch supplied with the cycle computer seemed to fail quickly in actual use. A larger, more robust one (COTO RI-48A, COTO Technology, Providence, RI) was used to replace the original part. A 0.1 μF ceramic capacitor was also placed in parallel across the reed contacts to remove high frequency noise from the tachometer circuit. The reed switch was held in place, parallel to the gear shaft and centered with the magnet with hot-melt glue. The cycle computer cable secured away from the moving parts by hot melt glue.

Modifications and the set-up for torque measurement: Torque measurement on the shaft of a rotary mixer is not readily accomplished for classroom demonstrations. Although strain-gage based industrial torque transducers are readily available, they are expensive and not easily incorporated into existing machines, especially consumer appliances. Space must be available along the shaft to attach the device and anchor it, and that is rarely the case. To measure torque using direct force is possible if the force used to resist the mixing shaft can be coupled into the outside container of the mixer, and that is the approach we use. By modifying the bowl cover to become free-floating, the mixing torque must be overcome by a restraining force applied to the lid. It is that force that we measure by means of an electronic lab scale. The force is applied to the scale as a lifting force through a string and pulley arrangement (Figure 6). Since it is a lifting force, we must either use an electronic scale capable of reading negative forces, or use a ballast weight. In this case, the string is tied to the weight, and as force is applied, the initial scale reading of the weight becomes smaller. The difference between this initial weight and the indicated weight is the restraining force on the lid. The torque then was calculated by multiplying the force with the distance between the center and the side of the lid. Many electronic scales have outputs for data logging, which allow for automation of the data collection run. This can result in more detailed (and even real-time display of) torque-vs.-time curves for the fluid under study. Obviously, electronic data logging and other improvements can be implemented as desired, but our initial goal is to allow multiple experiment stations to run simultaneously in a classroom setting, so we describe here what might be considered a minimal system. As such, we use readily available lab apparatus found in any food or process engineering laboratory: electronic scale, calibration weights, ring stands and clamps. The ice cream maker lid was modified to allow the mixing torque to be coupled to the outside of the machine. It is expected that most models utilizing a fixed paddle and rotating bowl can be modified to allow this. The stationary paddle is also required because it allows temperature probes to be inserted completely into the working fluid. In a rotating-paddle design, the probes would be swept away by the paddle, and there is no simple way to obtain temperature data.

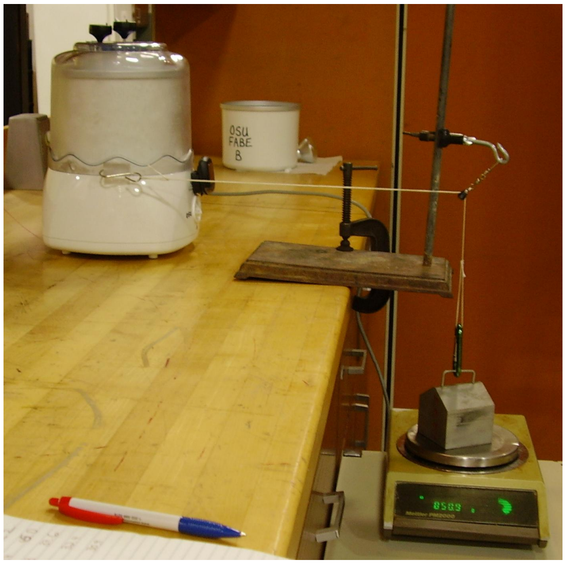


Figure 6. Set up to measure mixing force

The mechanics of the experiment are quite simple. The string is tied to the floating lid of the ice cream maker and looped over the pulley such that it lifts the weight sitting on the top of the electronic balance. It is recommended that the string be kept horizontal from the appliance to the pulley and vertical to the weight. We did this by placing the scale on a small cart in front of the lab bench. The top of the cart was lower than the bench top, as shown in Figure 6. The string should be tangent to the lid surface at the point of attachment as shown in the figure. An initial adjustment is necessary to tighten the string slightly. The initial weight reading needs to be corrected.

Procedure for ice cream experiment: Students followed the procedure outlined below during the laboratory to collect temperature, rpm, and rotational force.

- Weigh the ingredients and put all ingredients in freezer bowl
- Weigh a fixed volume of the ice cream mixture
- Place the ice cream mixture in the ice cream maker bowl (kept in the freezer at -20°C).
- Assemble the ice cream maker
- Place thermometers in the lid.
- Turn the ice cream maker on and collect temperature (center and side), mixing speed and mixing force data
- After 30 minutes, weigh a fixed volume of the ice cream

Results and Discussions

Formulation of ice cream using material balance concepts: Students were given a pre-lab assignment to calculate the amount of individual ingredients to prepare the 0.7 kg of vanilla ice cream for given requirements. The ingredient composition and the fat content requirement for ice cream specified for students are outlined in Table 1. Vanilla extract and salt are considered pure components and will comprise 0.86% and 0.2% of ice cream mixture respectively.

Table 1: Composition of ingredients and ice cream mixture

Products	% Fat	%Protein	% Water	% Carbohydrate
Heavy cream	36		64	
Whole milk	3.2	3.2	88.8	4.8
Sugar				100
Ice cream mixture	10.47	1.87	67.1	19.5

Students were asked to apply material balance concept to set up simultaneous linear equations that can be solved to obtain the amount of each ingredient (Figure 7).

Fat Balance:

$$(0.36)\ HC + (0.032)\ WM = (0.104)\ (700)$$

Carbohydrate Balance:

$$(0.048)\ WM + (1.0)\ S = (0.197)\ (700)$$

Water Balance:

$$(0.64)\ HC + (0.888)\ WM = (0.671)\ (700)$$

Figure 7. Material balance equations

Students solved the simultaneous equations based on the matrix concept by using MATLAB software (7.01, The Mathworks Inc.) to determine the amounts of heavy cream, milk, sugar, vanilla, and salt that must be used to make the ice cream (Table 2).

Table 2. Amount of ingredients to produce 700 g of vanilla ice cream

Ingredients	Amount (g)
Heavy cream	166
Whole milk	409
Sugar	118
Salt	1
Vanilla	6
Total	700

Calculation of heat removed: Students were asked to plot temperature data collected as a function of time during ice cream processing (Figure 8).

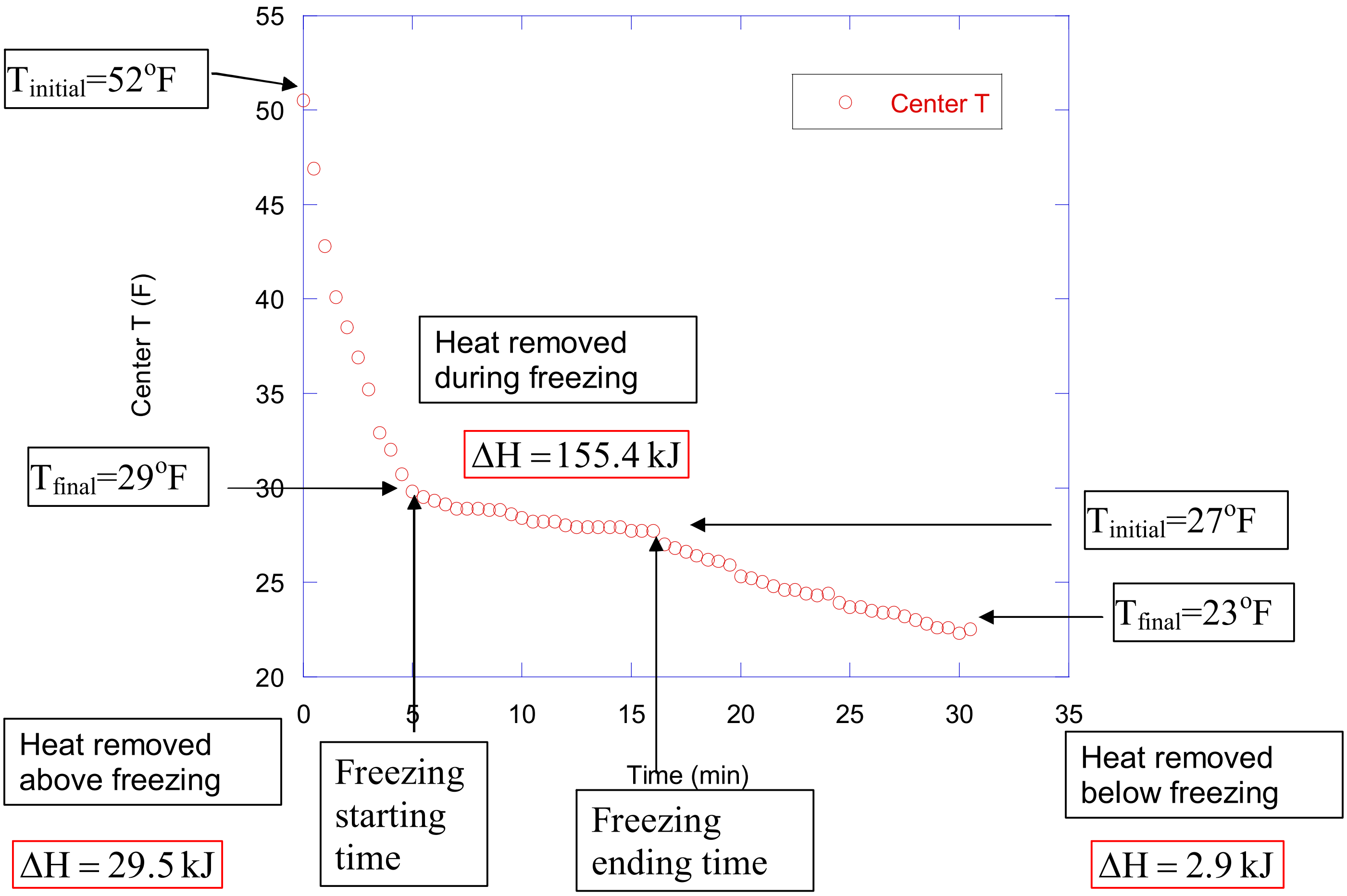


Figure 8. Heat removed based on center temperature. Heat capacities for ice cream above and below freezing are 3.3 kJ/(kg °C) and 1.88 kJ/(kg °C) respectively.

Figure 8 also demonstrates the freezing point depression as the start of freezing corresponds to 29 °F (-1.7 °C) but not 32 °F (0 °C). It is also clear that during freezing, the heat removed does not reduce the temperature but it is used to remove the heat corresponding to the phase change in this case going from liquid to solid phase. The ice cream also presents itself as an interesting system to teach students because the freezing point depression increases as the ice cream system becomes concentrated due to freezing of water. Therefore, in Figure 8, we do not see a horizontal (constant temperature) freezing process. Instead, we observe approximately 2 °F (1.1 °C) change in the freezing point of ice cream during the phase change.

Rotational force and rotational speed measurement: Students were asked to collect the mixing speed and the rotational force during ice cream processing. Figure 9 was constructed by plotting mixing force, mixing speed, and center temperature versus time during ice cream processing.

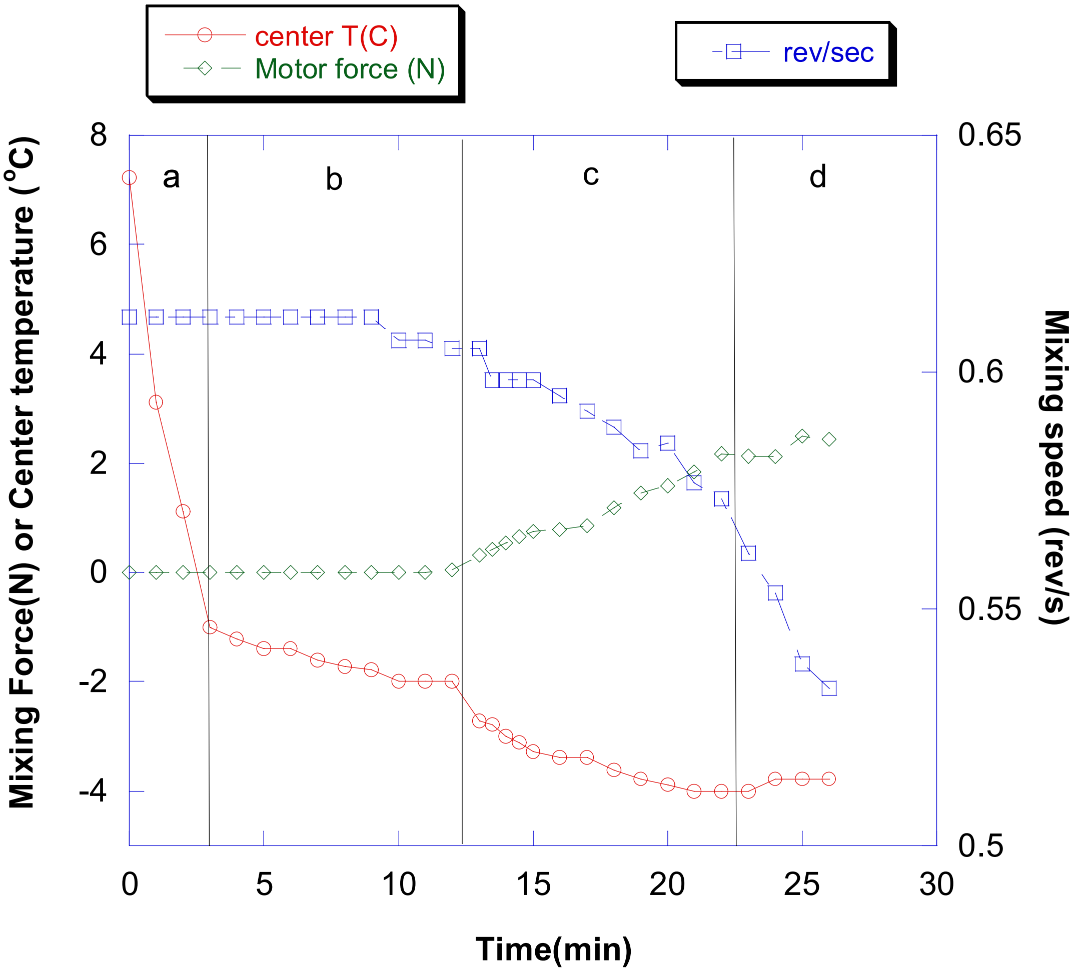


Figure 9. Mixing force, mixing speed, and center temperature of ice cream maker

We can identify four regions on the figure 9. Region *a* corresponds to the cooling of the ice cream mixture during which temperature decreases sharply but mixing speed and mixing force are constant. In region *b*, phase change progresses with small changes in mixing speed and mixing force and a slight decrease of temperature due to latent heat removal. Upon completion of the phase change, we observe an increase in mixing force with a concomitant increase in mixing speed due to increasing viscosity of the system in region *c*. A decrease of temperature also occurs in region *c* because the heat removed is the sensible enthalpy of the solid system. In region *d*, the temperature decrease stops because the heat removed from the system equals to the heat generated by the friction due to mixing as well as the heat removal from the freezer bowl is decreased due to warming of the freezer bowl.

References

Clarke, C. 2003. The physics of ice cream, Physics education, 38(3):248-253.